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Ethical, legal, social and economics issues of graphene

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1. Introduction

The term graphene was adopted in 1962, from the junction of graphite with the suffix—eno, due to the existing double bond. However, graphene was discovered in 2004 by researchers at the University of Manchester [1,2]. Andre Geim and Konstantin Novoselov, in 2010, were awarded the Nobel Prize for their experiments regarding the carbon-based nanomaterial graphene [3]. Graphene is a nanomaterial composed of the thinnest organic leaf that can exist with only one atom thick, transparent, and with carbon atoms arranged among themselves in a two-dimensional hexagonal network [4,5]. It consists of a flat monolayer of carbon atoms, organized in hexagonal cells with hybridized atoms in the sp^2 form, resulting in a free electron per carbon atom without orbital and making the graphene a material used in various applications [6]. Nanomaterials are nanometre-sized structures, with extraordinary physical and chemical properties and exceptional large specific surface areas that have improved detection sensitivity and miniaturized devices in bioanalytical procedures [7–9].

In this context, the electronic structure of graphene results in properties that reflect a mechanical resistance greater than that of steel, electronic mobility higher than silicon, thermal conductivity higher than copper, a surface area greater than that observed for graphite and even a lighter material among others. The surface of pure graphene normally interacts with other molecules via physical adsorption (π - π interactions) [10,11]. The thermal conductivity of graphene at room temperature can reach 5000 W/mK, which suggests potential uses for thermal management in a variety of applications. Also, graphene can also absorb a fraction of 2.3% of light [12].

Among the properties mentioned, graphene can also be used in applications such as polymer-composite materials, photo-electronics, field effect transistors, electromechanical systems, sensors and probes, hydrogen storage and electrochemical energy systems [7,8,13]. Also, graphene electrodes can increase the capacitance of supercapacitors by 20–30% [14]. Therefore, graphene has a great advantage in electrochemical applications, mainly due to its non-toxic attributes and conductive properties, in addition to being environmentally beneficial.

It is also noticed that the incentives for innovation in the form of tax incentives have become a trend worldwide and Brazil has not been an exception, especially concerning the research of nanomaterials such as graphene. Among the possible applications and innovations of graphene that could change the world, we know today are the use of graphene to produce a touch-sensitive, flexible, transparent, and unbreakable tablet and smartphone screen. It would replace the ITO (tin oxide doped with indium) currently used in sensitive screens; Acceleration of the internet, as it has been proven that graphene can convert optical to electrical information at a speed about 100 times faster than electrical converters; In this sense, in July last year, researchers from the British Universities of Bath and Exeter used optical switches made based on graphene that increased the data transmission speed by 100 times. There is also an extremely thin graphene antenna made by scientists from the Georgia Institute of Technology (USA) that allows 128 GB (or 1 terabit) to be transmitted in just 1 s, 1 m away [15].

In this context, research with graphene also led to the creation of the Graphene Flagship Consortium, a European group led by Nokia that includes 73 other partners, including universities and companies from various sectors, all interested in exploring the capabilities of graphene. In addition to Nokia and Samsung, IBM and SanDisk scientists are experimenting with the material.

Another study with graphene showed that the company Marcopolo intends, by the end of this year, to start tests with the application of graphene in new bus components. Thus, the objective is to reduce the total weight of the vehicle and expand and guarantee structural resistance, such as the possibility of using and introducing 100% electric or hybrid motorized vehicles that are occurring in the global automobile industry.

In the biomedical area, for example, the use of graphene can be used to make flexible and lightweight prostheses, in addition to implants. Also, it also has antibacterial properties [16]. The objective of this chapter is to present social, economic, ethical, and legal issues involving graphene.



2. Research using graphene and social issues

The largest research institute in the field of graphene in Brazil belongs to a private institution, MackGraphe (Center for Advanced Research in Graphene, Nanomaterials and Nanotechnologies at Universidade Presbiteriana Mackenzie) and is funded by public entities, such as Fapesp (Fundação de Amparo à Research of the State of São Paulo), CNPq (National Council for Scientific and Technological Development), BNDES (National Development Bank) and Finep (Financier of Studies and Projects). In this context, the advancement in research related to graphene in Brazil is of paramount importance due to the presence of one of the largest reserves of graphite in the world being present in the country. Since the price for extracting this nanomaterial is small, it is true that in 1 kg of graphite (US\$ 1) it was possible to extract 150g of graphene, marketed at US\$ 15 thousand. Brazil also has great potential for the use of this material due to its production capacity, and occupies the fourth position in the world rank among the countries that produced the most graphite in 2017 according to the American institute United States Geological Survey.

In China, a Zhejiang University developed or called a graphene aerogel. It is extremely light, with impressive properties as thermal insulators. With a density of only 0.16 mg per cm^3 , the material was tested as an antidote against alkali-aggregates, as an anti-corrosion coating for mixed structures (concrete and steel) and as a thermoacoustic insulator. With high mechanical resistance and high elastic recovery capacity, aerogel is already considered the lightest product developed in the laboratory. Aerogel is low-density materials in the solid gel state, with the liquid component replaced by gas. It is important to

note that, although the graph holds great promise for creating construction materials for the future, it has a deviation: at least for applied applications, it probably cannot be used alone. Therefore, building materials created in graphene may be a little further apart, although research is advancing rapidly. As a highly polluting and waste-generating industry, find greener ways to create a crucial breakthrough in reducing carbon emissions around the world, and therefore help protect the environment.

Recently, it was reported that a group of researchers from the University of Manchester, in the United Kingdom, created a kind of graphene “sieve” capable of transforming sea water into drinking water. This creation is fundamental in society since there are millions of people worldwide without access to drinking water and the tendency is that water scarcity will only increase over the years.

In this sense, there is also a diversity of other research that can benefit society with the use of graphene. Among these researches we can highlight: the Technical University of Munich, Germany, which has a team of physicists who are using the special properties of graphene to produce key elements of an artificial retina [17]. Retinal implants work by converting incident light into electrical impulses that can be sent to the brain via the optic nerve. In the brain, the signals are then converted into images, allowing blind people to see [17].

In Oceania, there is Sleepyhead, part of The Comfort group, the largest manufacturer of bedding and foams in the region made up of Australia, New Zealand and New Guinea that invests in research, which results in innovations such as the introduction of graphene in the foam of the company’s mattresses [18]. In Iran, with the increased incidence of diabetes, researchers at the University of Technology in Amirkabir designed a biosensor to detect a small amount of glucose in a urine sample. In this research, a combination of gold-graphene nanoparticles was designed without the use of polymeric materials to separate graphene nanoplates and reduce the likelihood of aggregation that results in high sensor sensitivity.

In this context, there is a graphene-based antibacterial paper for packaging food that was created at Shanghai University. It is only permeable to water and inhibits the growth of microorganisms. At the American University of Columbia, graphene was used to develop the smallest frequency modulated transmitter of which it has no information. Another study carried out at the University of California using graphene was developed to verify the reproduction of sound in headphones in extremely high quality [19].

In addition to the previously mentioned studies, an important additional advantage of graphene-based materials is their ability to effectively cross biological barriers, such as the blood-brain barrier. In this sense, graphene also has potential as a vehicle for administering drugs for anticancer therapy [20]. Also, researchers recently conducted research that suggests that graphene membranes could be used to perform DNA sequencing at the site. In this study, an artificial membrane in which the nanosized pores were pierced with an electron beam and are large enough to allow biomolecules such as DNA to enter. When the membrane is bathed in an electrolyte and a voltage is applied, a DNA molecule is attracted. The conductivity of the membrane is then changed depending on the exact configuration of the DNA.

Another health survey in China says studies in the past 4 years have identified graphene oxide as a potentially effective antiviral agent. Although none of the studies targeted the same pathogen responsible for the current coronavirus outbreak, one researcher says the conclusion is that graphene oxide can offer a platform to fight a variety of viral infections (such as the SARS-CoV-2 coronavirus) and possibly in the form of a coating [21].

Graphene and its derivatives also prove to be highly attractive for use in building supports for cell growth and scaffolds. In this sense, a study obtained an increase in the adhesion and differentiation of stem cells derived from human adipose tissue, when covering glassy substrates with GO films, when compared to uncoated substrates [22]. Another study demonstrated improvements in the adhesion and growth of osteoblasts on graphene-coated substrates when compared to uncoated substrates [23].

Another important study beneficial to society and which is in line with the Sustainable Development goal 13 that focuses its actions to maintain climate change and its impacts [7,10] is the use of graphene membranes developed to capture the excessive amount of carbon dioxide emitted into the atmosphere. Also, researchers at the University of South Carolina and Hanyang University in South Korea independently developed graphene-based filters that can be used to separate unwanted gases from industrial, commercial, and residential emissions [24].

The Journal of Environmental Science and Pollution Research published an article on treating organic liquid radioactive waste with the use of graphene. The objective of the research was to optimize the storage of these tailings, which occupy a lot of space in the deposits. According to the technique, it is possible to reduce the final tailings volume by up to 90%. In the research, graphene was used in the form of “quantum dots”, or quantum dots, which are semiconductor particles with nanometric size.

Thus, this high adsorption capacity, graphene quantum dot (GQD) manages to extract a large part of the particles suspended in the liquid medium, including the radioactive elements uranium and thorium, targets of treatment. This is because 1 g of the graphene used (in particles from 160 to 220 nm) is equivalent to an adsorbent surface area of up to 500 m^2 . In the experiment, 40% of the uranium present in the sample was adsorbed [25]. In addition, different types of magnetic nanomaterials have been used as support materials for environmental conservation [26]. We still have intelligent nanomaterials that have appeared as one of the materials for the modern world due to their exceptional thermal, electronic, optical and mechanical properties [27].

In this scenario, graphene represents a research area that has the capacity to generate innovative products, which can be reverted to countless benefits to society.



3. Economy and graphene

According to the market study by DataM Intelligence 4Market Research, the global graphene market is projected to reach R \$ 1.1 billion by 2025, with an average annual growth of 32%.

In June 2016, while each gram of gold cost R \$ 143, that of graphene was traded around US \$ 100 in the international market, that is, R \$ 346. The metric ton of graphene came to cost US \$ 1000, about 500 times more than graphite. Still in 2016, 1 kg of graphite cost US \$ 1. 150 g of graphene can be extracted from it, valued at least US \$ 15 thousand, a fantastic valuation. In this sense, the graphene market is expected to have the potential to reach up to US \$ 1 trillion in 10 years [28]. In 2017, regarding graphene, the market was estimated at US\$ 42.8 million, with an expected growth of 38% until 2025 [29]. Therefore, to be aware of the added value in the production of graphene, the price of 1 kg of graphite is currently approximately 2 dollars, while graphene costs between 150 and 250 dollars a gram [30].

In this context, the market studies available on the internet show a significant expected growth of the global market, with an expected average composite range. The data show that the forecast for economic growth considering applications of graphene is significant in the next 5–10 years, being 42.1% in the period 2014–22 for graphene [31]. However, the price of graphene is related to its quality. Graphene oxide powder is inexpensive

and was used to make a conductive graphene paper, for DNA analysis and other used applications of composites and biotechnology. Graphene oxide in solution is sold for 99 euros per 250 mL.

In several years, bulk prices of graphene may fall below the price of silicon, allowing graphene to enter all markets now dominated by silicon, such as computing, chip making, sensors, solar cells, etc. Meanwhile, graphene will continue to be used for applications of other materials. For example, silicon cannot be integrated into future flexible smartphones, because silicon is brittle and breaks when bent. In this sense, graphene offers a competitive solution.

Graphene prices are not as high as such a recent technology might expect. It is important to remember that carbon fibre, for example, was invented in the 1950s, but its use has not taken off for more than 30–40 years. A carbon fibre faced several challenges, including early market implementation and resulted in deficient products. Carbon fibre is now represented in advanced composite materials. The material survived the long struggle by finding applications that were not possible with other materials.

The graphene market has gained a vast potential for applications, thus reaching different stakeholders in the area. Many investments are being made by everyone involved with issues involving graphene to strengthen research in the area.

The energy and storage sector, according to the most current market studies, is where the greatest economic and technological potential for the application of graphene is concentrated, since this material has a high surface area, good chemical stability, and high electrical conductivity. According to researchers, these developments will allow a significant increase in the capacity for storing electricity in safer, lighter, and more compact batteries, covering a range of uses ranging from the electronics sector to mobility in electric vehicles.

Another area of application of graphene is in composite materials, where it is incorporated into a host material, such as polymeric, ceramic, or metallic matrices, modifying and improving its properties. In polymers, the incorporation of graphene makes it possible to obtain materials that are much more mechanically resistant, with the advantage of being able to introduce, simultaneously, other properties, such as gas impermeability and electrical conductivity. It can be used for the manufacture of aircraft parts, automotive vehicles, and civil construction materials, such as cement, refractories and paints [32]. In addition, graphene production influences mining and a

graphene production chain with enormous economic gains is to be expected. We also have applications for nanocomposite materials printed in analytical chemistry. [33].

The research led by the National University of Singapore (NUS) presented an economically and industrially viable strategy for producing graphene. The new technique addresses the long-standing challenge of an efficient process for the large-scale production of graphene and opens the way for the sustainable synthesis of the material [34].

In this sense, the conventional method of graphene production uses sound energy or shear forces to exfoliate the graphite layers and then disperse the layers in large amounts of organic solvent. As the insufficient solvent causes the graphene layers to reconnect to graphite again, the production of 1 kg of graphene currently requires at least one ton of organic solvent, making the method expensive and environmentally hostile [34]. However, the NUS-led development research team, on the other hand, uses up to 50 times less solvent. This is achieved by exfoliating the pretreated graphite under a highly alkaline condition to trigger flocculation, a process in which the graphene layers continuously group together to form a graphene paste without having to increase the solvent volume. The method also introduces repulsive electrostatic forces between the graphene layers and prevents them from reconnecting.

In the USA, a group of scientists from the USA and South Korea has developed a new type of LED that combined “one-dimensional vertical superlattices” with two-dimensional graphene sheets to create a tough LED with optical and electrical properties. As graphene is gradually incorporated into LED manufacturing, energy consumption will be reduced by 20% compared to ordinary light bulbs. In addition, the duration of the LED it uses is about 25 years [35].

All applications in relation to graphene can bring numerous benefits to society, but not all are at the same stage of investigation, evaluation, standardization, and use. Research indicates that the application of graphene on the market will reach maturity in the next 10 years and that many products for consumption are expected by 2030.

In this scenario, one of the concepts of economics, which provides us with an idea of the importance in development, is the understanding that individuals are subject and respond to incentives and that they can change their decisions/actions. In this sense, we have the right that, in general, it is a tool that acts on the behaviour of individuals, so it acts as an incentive, whether to do something or not.



4. Reflections on legal and ethical issues of graphene

It is essential that intellectual property is used in a way that respects its social function. In other words, it should not function as a mere instrument for enriching the few when the products in question can provide significant social improvements—as is the case with products created from graphene. In addition, it is essential that there is a deepening in relation to the environmental regulation of graphene and its possible damage to the environment [36,37].

In the face of the graphene revolution, a multitude of aspects should be thought and studied as quickly as possible, including the regulatory framework and the legal concept of this novel material, thus guaranteeing a scenario of economic freedom with greater legal certainty.

Moral and ethical issues need to be analysed in the discussion regarding the manipulation of graphene with the effective participation of the population. The top-down approach is unfortunately used in some sectors, such as the medical sector. However, the ethical dimension needs to be considered to scientific and the regulatory aspects of innovation in relation to graphene. Ethics committees need to be formed to provide advice on the moral issues of graphene, to mediate the public and decision-makers in terms of transparency and democracy. This approach needs to be summarized in ethical, legal, and social aspects. These aspects considering graphene comprise a wide range of aspects, such as issues of privacy, acceptance, human health, responsibility, regulation, and control.

However, the management of graphene faces challenges such as regulatory development and marketing that is carried out in relation to innovations involving graphene, as well as the diversity of products that reach the market requiring differentiated and flexible approaches. In this sense, risk management actions are necessary and standardization of regulatory measures considering different countries is a challenge. In this sense, scientific awareness regarding manipulation and exposure to graphene stands out. Therefore, it is also necessary to have an exchange of information between the interested parties, thus finding a way to have a debate on the uncertainties and discoveries.

Therefore, all actors, such as researchers, industry, policymakers, and legislators, need to engage in innovation processes to meet ethical and social needs and thus support and learn from each other. In this sense, this debate is necessary to identify risks and uncertainties.

In Brazil, the National Secretariat for Graphene (SENAGRA) must be responsible for devoting themselves *pro tempore* to the joint elaboration of a regulatory framework and a national policy for the exploration of graphite and the production of graphene in the country. Evidently, the legal concept of graphene should not be at the mercy of the Judiciary, since the legislator can idealize a legal concept of graphene in order to provide a greater degree of legal certainty at the regulatory level—necessary for sustainable economic development in line with the general principles of economic freedom—of intellectual property—essential for the protection of trademarks, patents and industrial secrecy—and of tax and consumer relations—fundamental to ensure the defence of the environment, as well as rights and guarantees “citizen-taxpayer-consumers” in the face of possible abuses by the “Fiscal State” and Companies.

The European Union’s incentive policy aimed at Research, Development, and Innovation (RD&I) has high economic resources but only directed to technical, scientific, and endogenous research. As we have seen in Brazil, the European Union does not reserve economic resources for exogenous research directed at graphene in the fields of Law, Sociology, and Economics; Economic freedom and legal certainty depend on due respect for industrial secrecy and trademarks and registered patents.

In general, technical concepts from the field of RD&I are insufficient to ensure legal certainty for tax, market, and consumer relations. That is why it is recommended to design specific and determined legal concepts of “graphene” for the purpose of defending the State, individuals, and companies to avoid future and unwanted judicialization of this concept by the courts.

In addition, the advent of nanoscience and nanotechnology brought in tow promises of a true revolution in customs and the way we relate to things, and again carbon, with its two nanostructures—nanotubes and graphene—played a central role in that expectation.

It is also necessary to pay attention to the large number of commercial samples that are, in fact, “false graphene” (from English *fake graphene*), where materials that do not have characteristics of graphene are erroneously classified as such. A recent systematic study analysed 60 companies that produce graphene (does not include GO and rGO) in the world (Americas, Asia, and Europe), and showed that a large part of them sell “fake graphene”, of very poor quality, basically consisting of graphite [38].

However, even with so many benefits of graphene, an issue that needs to be discussed is its toxicity already described in different literature reviews

[39–41]. In vitro studies show concentration and time-dependent cytotoxicity (apoptosis) in lung cells (BEAS-2B), ROS generation, cytotoxicity, and mitochondrial damage in neural cells (PC12), macrophages, and epithelial cells. Inflammation has also been observed in THP-1 cells. Graphene functionalization decreases toxicity compared to the simple counterpart. Dimension is also a factor, where smaller leaves are more toxic than larger leaves of the same thickness. The cellular internalization mechanism of different compounds in the graphene family (for example, graphene, graphene oxide, reduced graphene oxide) may be different. Genotoxicity has also been observed in human fibroblast cells for graphene oxide. According to Arvidsson et al. [40] the in vitro concentration of cells with no observed effect varies between 0.01 mg/L for metabolic activity and 20 mg/L for the viability of human fibroblast cells. However, compounds in the functionalized graphene family generally have less toxicity.

In addition, there are studies available on the exposure of workers to materials from the graphene family, especially at the industrial level [42]. Also highlighted in this context, is the knowledge about the possible abundant use of graphene in composites, its persistence, and hydrophobicity, as well as its substantial toxicity according to studies carried out, thus implying that graphene must be considered a potential environmental and health risk. However, due to the great interest in the use of graphene, research on it faces many challenges like other new research materials. In this sense, research on graphene and related hybrids creates many questions and new ethical concerns may arise when scientific unknowns become better known and public reluctance becomes more apparent considering the increase in scientific data.

However, in order to facilitate communication between organizations, researchers, industries and other stakeholders, the ISO/TS 80004-13: 2017 standard was published in 2017, which lists the terms and definitions for graphene and related two-dimensional materials, which includes terms, production methods, properties and characterization [43]. One of the great challenges of graphene production is to find a method that obtains a high degree of purity and is also applicable on a large scale. Among the methods described in the literature are mechanical exfoliation, chemical exfoliation, and chemical vapour deposition. In this context, several authors use different terminologies to talk about the same type of graphene. However, the Carbon magazine launched an editorial to establish standards to be followed in the denomination and correct classification of materials in the graphene family.

Researchers at the University of Caxias do Sul (UCS), RS, Brazil, develop their method for producing graphene with high purity. Initially on a small scale, production is focused on the use of material for scientific research produced at the institution, in the areas of nanotechnology, regenerative medicine, advanced coatings and military security. The mastery of the productive technique, however, can allow the development of other applications in several areas of the material—the lightest and most resistant that exists, with excellent thermal and electrical conductivity—can be implemented.

Research at UCS on the use of graphene are distributed in different areas:

Regenerative medicine—studies future applications in the areas of materials and health. Among the perspectives is the creation of hybrid polyurethane hydrogels with graphene, capable of modulating chemical cell environments. This would open up conditions for use in regenerative medicine, even contributing to the recomposition of tissues in the human body.

Nanotechnology—performs studies with graphene oxide for the production of supercapacitors, components used in electronic circuits. The aim is to improve the data processing capacity and memory of devices such as cell phones, tablets and notebooks, as well as increasing the charge and storage speed of batteries.

Oil absorption—research is carried out with carbon nanostructures applied to polymers. With the introduction of graphene, studies show an increase in the quality, efficiency and resistance of touch screens, solar cells and solvents—whose oil absorption capacity is tripled with the addition of graphene.

Intelligent fabrics and military security—involves the application of the material in airgel, can give rise to intelligent fabrics, generating garments with high thermal insulation capacity. Finally, UCS also carries out, for the Brazilian Army, research for the insertion of graphene in vests and helmets, aiming at increasing the resistance to the impact of these safety equipment.

In addition, Graphene Flagship has released a manual on the various processes for making graphene, considered the “material of the future”. The writing of this book, which is considered a European Union flagship project, involved 70 researchers from the European consortium. With the manual *Production and processing of graphene and related materials* [44], the authors intend to achieve mass production of graphene and make it faster to reach consumers [45]. The manual has nine chapters that summarize the different ways to synthesize and manufacture graphene and other

two-dimensional materials. The chapters of the manual are as follows: bottom up, top down, processing of dispersions, graphene growth on SiC, CVD, PVD and MBE, graphene transfer, placement and decoupling from substrate, growth and transfer of other layered materials, functionalization of GRMs, characterization methods. The manual is one of the three science anchor projects in the European Union, alongside Human Brain and Quantum. These have helped Europe to compete with other global markets in research and innovation. In this sense, several European centers are already working, not only in the preparation of standards that can be used as a reference but also in the standardization of protocols for graphene.

Therefore, scientifically based education with a greater number of researchers is necessary, but the general population needs to participate and become aware of the issues surrounding graphene so that there is responsibility in the handling and use of this material with a view to meeting needs in relation to technological potential. The methods need to be based on evidence so that we can understand the issues investigated and interventions. In this way, these methods can be used so that there is the interaction of the interested parties. Therefore, ethical, and legal standards need to be considered to increase the acceptance of the application and acceptance by society.



5. Final considerations

The deepening of research on graphene follows the market trend in making the production of nanomaterials on an industrial scale feasible for applications in several areas. These applications include the electronics, textile, plastics, civil construction, and automotive industries, as well as promising applications in the field of medicine and energy production. In addition, graphene is already known as one of the elements that will revolutionize the technology industry as a whole due to its strength, lightness, transparency, and flexibility, in addition to be an excellent conductor of electricity. Graphene is also considered a perfect material to unite the research sector and the industry, considering that the potential market is huge, as well as profitability. However, it is important to highlight that it is still a challenge in the technological and financial area for it to be able to produce graphene nanocomposites in scale.

However, it is necessary to implement adequate regulation and quality control protocols that guarantee reliability in the graphene production

process. In this sense, Brazil has installed capacity in Universities and Research Institutes to meet and foster demands in the area and can be competitive worldwide.

However, considering the precautionary principle, from available data, we can conclude that graphene can also cause toxicity through different routes of exposure in humans and aquatic organisms and plants. However, currently in the literature, data are insufficient to draw conclusions about all the potential risks of the graphene family. Therefore, we have two groups of opinions about graphene, one of which says that graphene materials are bio-compatible with the number of studies focused on biomedical applications, and the other group reports that they have studies showing adverse effects in terms of biology and cytotoxicity in relation to graphene.

Therefore, the development of research related to graphene can promote the diffusion of technical and scientific knowledge in a promising area, since the main uses of graphene are concentrated in energy generation and storage systems. The use of graphene as an integral part of the electrodes of a battery, for example, can solve the limitations of both batteries and conventional supercapacitors.

In this sense, the importance of investigating and deepening research on graphene is because the market trend for the coming years points to the production on an industrial scale of nanomaterials and applications in various areas.

WEBSITES

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